Modeling Indoor PM2.5 Air Pollution, Estimating Exposure, and Problems Associated with Rural Indonesian Households Using Wood Fuel

by Haryono S. Huboyo

Chapter 20
Modeling Indoor $PM_{2.5}$ Air Pollution, Estimating Exposure, and Problems Associated with Rural Indonesian Households Using Wood Fuel

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Abstract A large segment of rural Indonesian households still use wood as their main fuel for cooking. In this study, we modeled the indoor air pollution implications and estimated exposures using $PM_{2.5}$ concentrations in kitchens and living rooms with time activity information by season at villages in West Java Province (Lembang, highland) and in Central Java Province (Juwana, coastal area). The $PM_{2.5}$ concentrations were measured 24 h using UCB particle monitors. Modeling indoor air pollution was conducted using a single box model. The average daily exposures in Lembang and Juwana were 0.24 (mg/m^3) and 0.1 (mg/m^3), respectively. The relative risks (RRs) (95% CI) of cardiopulmonary diseases due to wood fuel use were, respectively, 1.52 and 1.44 for Lembang and Juwana. The adjusted RRs for cardiovascular diseases were, respectively, 1.47 and 1.39 for Lembang and Juwana. The ratio of simulated concentrations to actual concentrations was better for the Lembang site, 0.9 and 1.7, compared to the Juwana site, 1.13 and 1.8, for the wet and dry seasons, respectively. Overall, this model is quite useful to preliminarily assess the indoor air pollution that might occur if housing parameters are well characterized. It seems that this model has greater accuracy for predicting moderate indoor kitchen concentrations, i.e., those around 1 mg/m^3. Adoption of dual fuel energy (LPG-wood fuel) in rural areas is mainly driven by economical motive. To solve the problem comprehensively, it needs long-term, medium-term, and

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short-term program. The immediate action (short term-program) is to mitigate indoor air pollution within rural households as much as possible by ventilation arrangement and good cooking practice implementation.

20.1 Introduction

The use of firewood as the primary fuel is still dominant in developing countries (Heltberg 2003; Smith et al. 2004). In Indonesia, based on data from the Ministry of Energy and Mineral Resources, at least 243 million barrels of oil equivalent (BOE) of biomass were consumed nationally in 2010, a share of more than 74% of total household energy consumption (CDIEMR 2011). According to historical data, this consumption is expected to continue to rise despite the oil into LPG conversion program that has grown from year to year.

The International Energy Agency estimated that in 2004, 95% of rural Indonesian people still used biomass fuel (IEA 2006). More quantifiably, Kamaruddin (1998) estimated that annual per capita wood consumption was about 0.88 m^3 of fuel wood/head/year, the equivalent of about 17.7 MJ/person/day. The persistent use of wood fuel, despite households having already received LPG stove packages, is a safety concern (i.e., fear of explosion or fire with the use of LPG, particularly by the elderly), as are fuel accessibility, fuel prices, and the taste of the LPG-cooked food.

The prolonged use of firewood for cooking eventually has a health impact on the cookers, as the resulting smoke particles are generally in the inhalable size range, with peaks of 0.1–0.2 μm (Kleeman et al. 1999). The health impact associated with the use of firewood has been widely studied in the developing world. A summary can be found in Fullerton et al. (2008).

The concentration levels of pollutants may vary significantly over time and space because of the large variety of sources, the operation method of some sources, and the various ventilation facilities present. Significant variations may also occur from room to room in a house; the living arrangement could be a factor when assessing indoor air pollution levels. Clark et al. (2010) pointed out the importance of housing characteristics, which eventually affect ventilation, plus of stove quality, when undertaking large-scale exposure studies of indoor air pollution. In this case, measuring $PM_{2.5}$ concentrations in the kitchen and living room could give the best estimates of the health impact on the inhabitants.

This research's aim was first to identify the risk to the cooks due to $PM_{2.5}$ exposure as the result of wood fuel use. Second, it sought to model the indoor $PM_{2.5}$ air concentrations derived from cooking activities in the distinctive kitchen environment. The third is to analyze the root problem and proposed recommendations related to Indonesian household using wood fuel.

20.2 Research Methodology

20.2.1 *Indoor $PM_{2.5}$ Measurements*

To reveal the indoor air pollution in both areas, we sampled households in each site during two seasons to determine the indoor $PM_{2.5}$ concentrations. The measurements took place in the kitchens of rural households for 22–23 h using inexpensive photoelectric monitors (UCB monitors). The UCBs were set in the middle of the wall in front of the stove. To minimize interference, the UCBs were hung at least 1.5 m away from the doors and windows and were 150 cm above the floor. These devices were already calibrated in a simulated kitchen as well as in the field with gravimetric-based principle devices. The UCB photoelectric chambers were cleaned after every five measurements, and prior to use, the UCB was zeroed in a Ziploc bag for at least 30 min. The detailed results of the $PM_{2.5}$ concentrations for both sites are explained elsewhere (Huboyo 2013; Huboyo et al. 2013). The locations for the measurements are shown in Fig. 20.1.

20.2.2 *Exposure and Risk Estimates for the Cooks at Both Sites*

We estimated exposures using $PM_{2.5}$ concentrations in the kitchens and living rooms as well as the outdoor ambient concentrations and combined the time activity information by season at the two sites. The average 24-h exposure to $PM_{2.5}$ for each person was estimated using a modified formula that had been originally proposed by Balakrishnan et al. (2004) and by Mestl and Edwards (2011). The exposure formula was:

$$E_w = \left(\frac{[Tc^*Ckc] + [Tk^*Ck] + [Ti^*Ci] + [To^*Co]}{Tc + Tk + Ti + To}\right)_w$$

$$E_d = \left(\frac{[Tc^*Ckc] + [Tk^*Ck] + [Ti^*Ci] + [To^*Co]}{Tc + Tk + Ti + To}\right)_d$$

$$E_{\text{total}} = \text{average}(E_w, E_d)$$

where

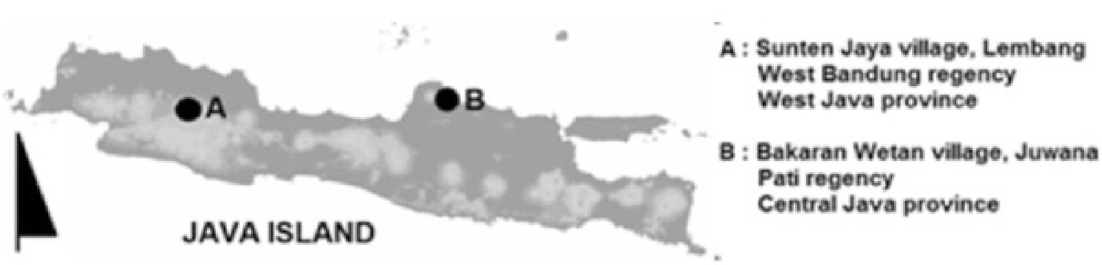

Fig. 20.1 The measurement sites

w: wet season
d: dry season
Tc: time spent in the kitchen while cooking, 1.84 h (wet season) and 2.32 h (dry season) in Lembang and 0.84 h (wet season) and 0.74 h (dry season) in Juwana
Ckc: kitchen concentration during cooking
Tk: time spent in the kitchen when not cooking (we assumed this to be 0.5 h/day for wood fuel preparation and other purposes)
Ck: average kitchen concentration other than during cooking periods
Ti: time spent in the living room (the remaining time after *Tc*, *Tk*, and *To*)
Ci: 24-h average concentration in the living room
To: time spent outdoors, calculated by estimating the worktime for householders, i.e., 7 h and 9 h, respectively, for Lembang and Juwana
Co: outdoor concentration during the wet and dry seasons

The equation was divided by ($Tc + Tk + Ti + To$ [24 h]) to estimate the 24-h average concentration exposure. This formula assumes the kitchen $PM_{2.5}$ concentrations are well mixed; the $PM_{2.5}$ concentrations in the bedroom are comparable to those in the living room; the time spent in the kitchen, living room, and outdoor do not change by season; the cooks also work in the fields; and the cooking duration in the morning and evening (particularly in the Lembang site) are comparable. The data used here were adopted from UCB measurements in Huboyo (2013) and Huboyo et al. (2013). The parameters used in the calculation are summarized in Table 20.1.

20.2.3 Indoor Air Pollution Modeling Using a Single Box Model

The indoor air concentrations during the cooking periods were predicted using a single-box model. This model assumes a well-mixed room with a single constant

Table 20.1 Parameters for estimating daily exposure of $PM_{2.5}$

	Wet season	Dry season		
Parameters	Lembang	Juwana	Lembang	Juwana
Ckc (mg/m^3)	2.01 (1.78)	1.09 (1.37)	1.16 (1.01)	0.78 (0.76)
Ck (mg/m^3)	0.24 (0.19)	0.12 (0.08)	0.13 (0.1)	0.09 (0.05)
Ci (mg/m^3)	0.12 (0.04)	0.09 (0.02)	0.18 (0.18)	0.07 (0.02)
Co (mg/m^3)	0.06 (0.00)	0.05 (0.00)	0.06 (0.03)	0.08 (0.01)
Tc (h)	1.29	0.84	2.36	0.73
Tk (h)	0.50	0.50	0.50	0.50
To (h)	7.00	9.00	7.00	9.00
Ti (h)	15.21	13.66	14.14	13.77
Daily exposure, E(mg/m^3)	0.21	0.11	0.24	0.10

Note: values in the parentheses are standard deviation emission source. It also assumes instantaneous mixing and no backflow into the room. This model considers stove performance and kitchen characteristics. The ventilation, represented by the air exchange rate, is the main parameter for pollutant removal; other removal mechanisms were assumed to be negligible. The model is adopted from Johnson et al. (2011). It is described mathematically as:

$$C_t = \frac{Gf}{AER(V)}\left(1 - e^{-AER(t)}\right) + C_0\left(e^{-AER(t)}\right)$$

where

Ct: concentration of $PM_{2.5}$ at time t (mg/m^3)
G: emission rate (mg $PM_{2.5}$/h)
AER: air exchange rate (/h)
V: kitchen volume (m^3)
t: time (h)
C_0: $PM_{2.5}$ concentration from the preceding time unit (mg/m^3)
f: fraction of emissions that enter the kitchen environment

The time interval of iteration was set in 1 min intervals to match with the monitored $PM_{2.5}$ in the UCB (also in 1 min intervals). The AER was estimated using the same formula as that found in Huboyo (2013). This AER did not consider the availability of the ventilation area. Instead, it was estimated by the slope of the least-square fit of the natural logarithm for the decay of CO concentration (McCracken and Smith 1998). In this study, the AERs were in the range of 0.2–3.23 h^{-1}. The fraction of emissions entering the kitchen environment was assumed to be 1 at both sites, since no chimneys were installed. The background concentration before cooking started was set as the initial C0. The emission rate was assumed to be constant throughout the cooking period. This rate depends on the stove power, stove thermal efficiency, and emission factors (fuel-based emission factors). The emission rate G (mg $PM_{2.5}$/min) was calculated as:

$$G = \frac{E_F}{E_D} P(\eta)$$

where

EF: fuel-based emission factor (mg $PM_{2.5}$/kg fuel)
ED: the energy density of the wood fuel (MJ/kg) (16 MJ/kg was assumed in Huboyo 2013)
P: stove power (MJ/h), 4832 W from the WBT test in Huboyo et al. (2013)
η: stove efficiency (18% based on the cold test in WBT, Huboyo et al. 2013)

We used 500 mg PM emission/kg wood fuel as the PM emission factor. This is the lower end of the emission factor of a simple wood stove, as depicted by MacCarty et al. (2010).

20.3 Results and Discussion

20.3.1 Risk Estimates for the Cooks at Both Sites

The average daily exposures in Lembang and Juwana were 0.24 (mg/m3) and 0.1 (mg/m3), respectively. If we assume the inhalation rate is 18 m^3/day for adults (Smith and Peel 2010), then the daily exposures correspond to daily doses (DD) of 4.36 mg and 1.85 mg $PM_{2.5}$ exposure, respectively, for the cooks in Lembang and Juwana. This average daily dose of $PM_{2.5}$ was used to obtain the relative risk (RR) for cardiopulmonary and cardiovascular diseases. The logarithmic relationship between RR and daily dose for cardiopulmonary (Cp) diseases and cardiovascular (Cv) diseases suggested by Pope et al. (2009) are:

$$\mathrm{RR(Cp)} = 0.1083 \times \ln(\mathrm{DD}) + 1.37, \mathrm{R2} = 0.87$$

The upper and lower 95% confidence limits are:

$$\begin{aligned} \mathrm{Upper} &= 0.1014 \times \ln(\mathrm{DD}) + 1.55, \mathrm{R2} = 0.86; \\ \mathrm{Lower} &= 0.1137 \times \ln(\mathrm{DD}) + 1.22; \mathrm{R2} = 0.80 \end{aligned}$$

$$\mathrm{RR(Cv)} = 0.0978 \times \ln(\mathrm{DD}) + 1.33, \mathrm{R2} = 0.89$$

The upper and lower 95% confidence limits are:

$$\begin{aligned} \mathrm{Upper} &= 0.0986 \times \ln(\mathrm{DD}) + 1.48, \mathrm{R2} = 0.86; \\ \mathrm{Lower} &= 0.0969 \times \ln(\mathrm{DD}) + 1.20, \mathrm{R2} = 0.89 \end{aligned}$$

The estimated relative risk (RR) can then be calculated as shown in Table 20.2:

Since the Lembang communities cook twice a day and have the worst kitchen environment, they have longer exposures (Tc) and higher pollutant exposures (higher Ckc) compared to the Juwana communities. This will ultimately make the pollutant daily dose higher compared to that in the Juwana site. The relative risk of cardiopulmonary diseases and cardiovascular diseases due to using wood fuel showed higher values in the Lembang site than in the Juwana site. Since most of the cooks are housewives, the cooks would be women of 30 years or more of age.

Table 20.2 Estimated relative risk (RR) due to wood fuel use for the cooks in two sites

Sites	24-h average exposure (mg/m^3)	Estimated daily dose (mg)	Adjusted RR [95%CI] Cardiopulmonary diseases	Cardiovascular diseases
Lembang	0.24	4.36	1.52 [1.38–1.69]	1.47 [1.33–1.62]
Juwana	0.1	1.85	1.44 [1.29–1.61]	1.39 [1.26–1.54]

The relative risk estimate of the cooks for cardiopulmonary diseases was quite lower than that estimated for India (Desai et al. 2004), which had been shown to be 3.20 [CI: 2.30–4.80]. However, it was almost comparable to the relative risk calculations made by Mestl and Edwards (2011) for Chinese wood fuel users, i.e., 1.51 [1.36–1.69]. In addition, the result for relative risk of cardiovascular disease in the Lembang site was also comparable to the 1.48 [1.34–1.64] found by Mestl and Edwards (2011).

The evidence of risk of COPD for women older than 30 years due to biomass fuel use is strong. Hence, exposure reduction is indispensable. It is therefore essential to promote good cooking practices and healthy kitchens among wood fuel users, who are still a high proportion of the population across Indonesia.

20.3.2 Modeling Indoor Air Pollution Using Wood Fuel

The results of simulated concentrations compared with actual concentrations are illustrated in Fig. 20.2. The ratios of the simulated concentrations to the actual concentration on average were 1.1 and 1.7 for the wet season and dry season, respectively. However, several samples from both sites had a large degree of uncertainty, i.e., their ratios showed 3–5. The actual emission rate varied widely, depending on the burning condition of the stove. Were we to keep this emission rate at a constant value and were we then to compare the minute-by-minute results between actual and simulated concentrations, the simulation results have a large amount of uncertainty (they either overestimate or underestimate). For example, in the L7 sample in the wet season, the variability of the actual emission rate was very high (the std. deviation was about 7 mg/m^3, while the simulation results showed only 0.7 mg/m^3). This high variability in the emission rate might be due to the cooks' behavior of blowing air into the stove, wood refueling, and wood fuel moisture. This model is sensitive to emission rates and kitchen volumes, accounting for about 50% of the variance in the kitchen concentrations. Therefore, these parameters greatly influence model accuracy. The AER contributes to about 10–25% of the kitchen concentration variability. It seems that this model has greater accuracy for predicting moderate indoor kitchen concentrations, i.e., those around 1 mg/m^3. The ratio of simulated concentrations to actual concentrations is better for the Lembang site, i.e., 0.9 and 1.7, compared to the Juwana site, i.e., 1.13 and 1.8, for the wet and dry seasons, respectively. Overall, this model is quite useful for a preliminary assessment of the indoor air pollution that might occur if the housing parameters are well characterized.

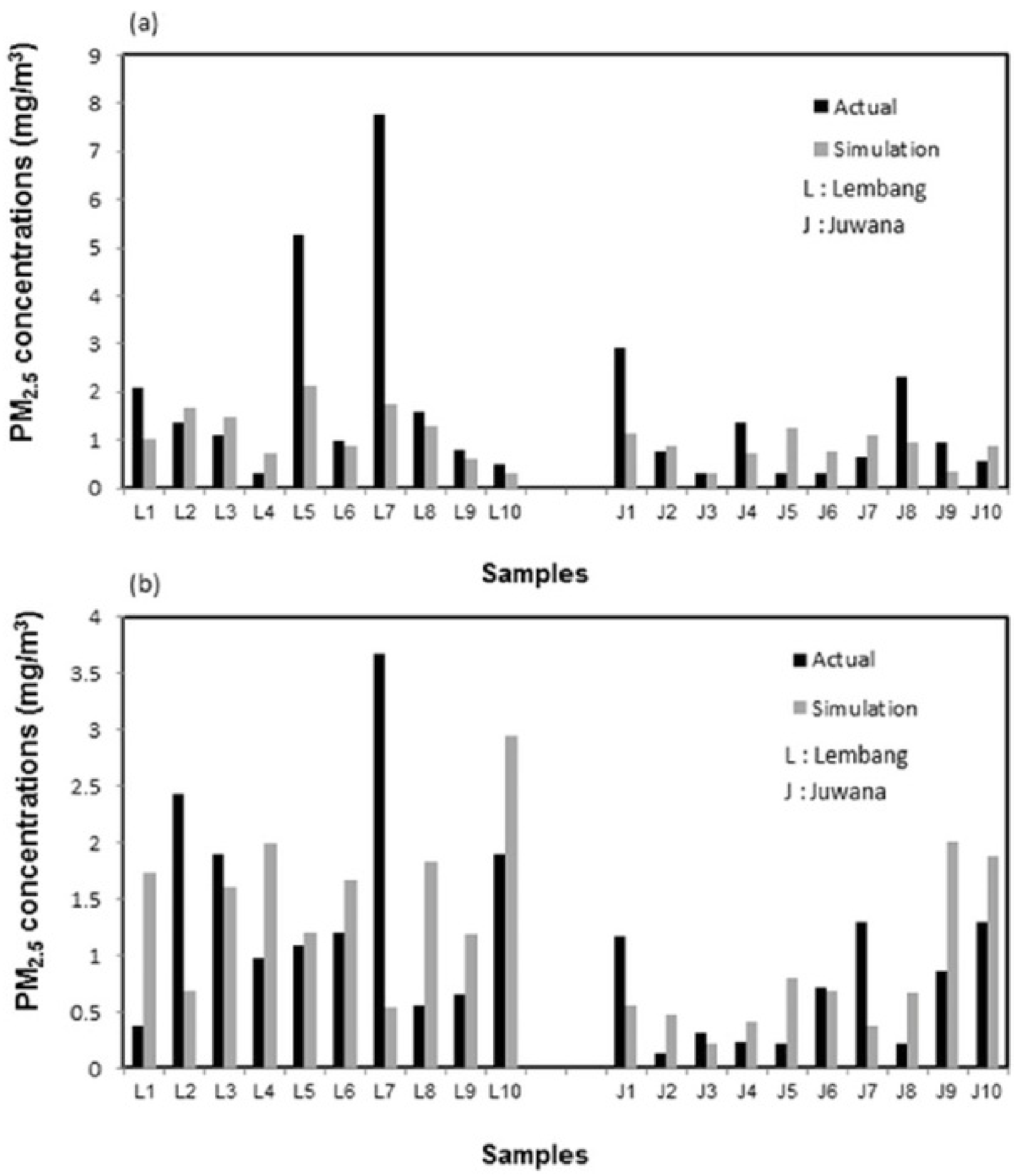

Fig. 20.2 Comparison of actual concentration and simulated concentrations during cooking periods in two seasons: (**a**) wet season and (**b**) dry season

20.3.3 Problem and Proposed Recommendation for Household Using Wood Fuel

Wood fuel will still dominate in the future energy supply for Indonesian rural households. Based on energy statistics, the household sector is estimated using biomass increase from 2000 to 2010 on average by 1.6% (CDIEMR 2011). Based on national social economic survey, the wood fuel user fractions were 69% in rural areas and 15% in urban areas.

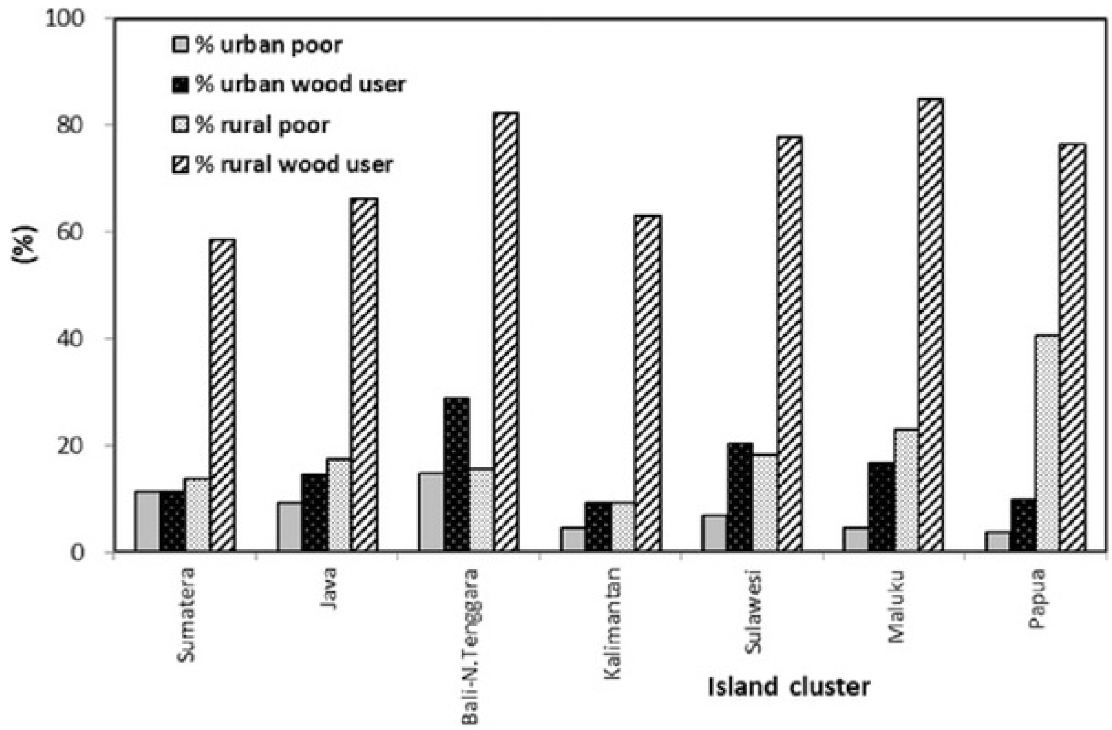

Fig. 20.3 Wood fuel users based on island (clustered provinces)

Likewise in other developing countries, some parts of the wood fuel users are located in urban areas in addition to huge consumers in rural areas (see Fig. 20.3). Interestingly many of these users, both in urban and rural region, are not simply categorized as "poor" or low-income households where for rural households it shows in high fraction. It seems culture and accessibility influenced the fuel choices of these affluent households.

Adopting modern fuel, i.e., subsidized LPG, would not necessarily leave wood fuel as household cooking fuel energy. Adoption of dual fuel energy (LPG-wood fuel) in rural areas is mainly driven by economical motive. This will have benefit to rural household cooking energy security in case of the disturbance of subsidized LPG supply. Moreover, the wood fuel is still required for heavy cooking such as boiling water and rice cooking. In fact, the wood fuel users were also not to be targeted of LPG fuel conversion.

Wood fuel users are generally categorized as low-income families, and then it is supposed that their lifestyle is not in healthy conditions. According to the survey by the Ministry of Health, Indonesia, about 83.2% of housing in rural areas are unhealthy compared to 67.5% in urban areas (NIHRD 2010). It is likely that wood fuel users have unhealthy households as depicted in Fig. 20.4. Unhealthy housing environment will exacerbate health effects related to indoor air pollution attributable to harmful pollutant exposure emitted from unprocessed wood fuel in a traditional wood stove.

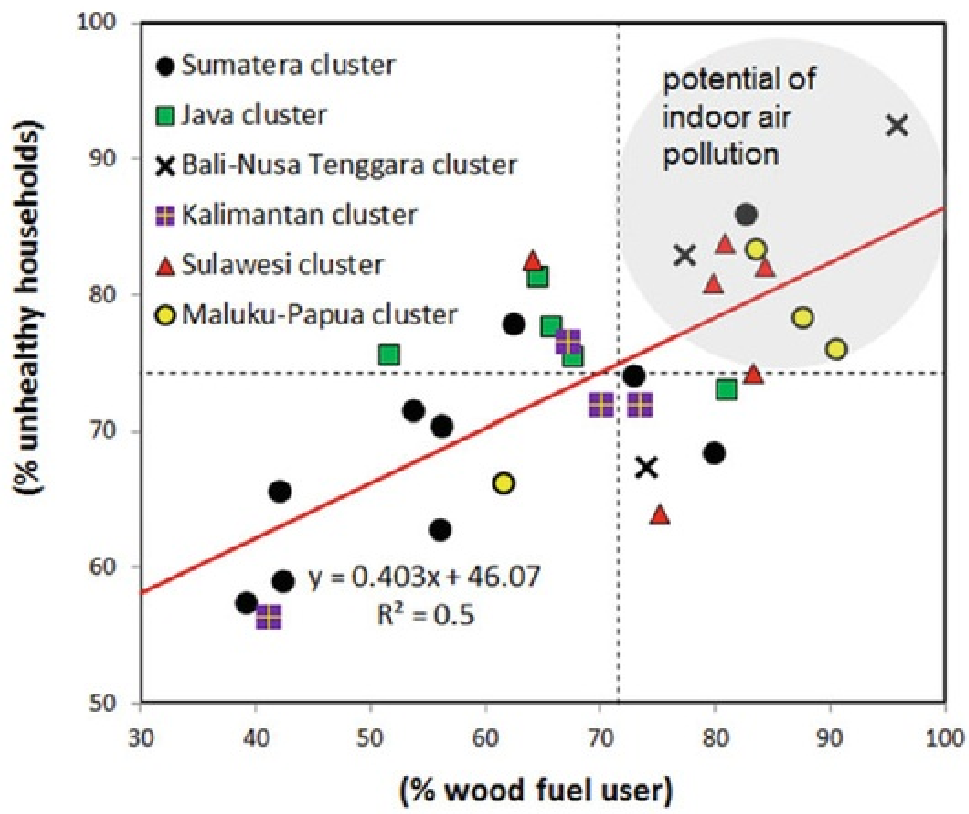

Fig. 20.4 Relationship between wood fuel user and unhealthy household at province level (grouped at island cluster based) (Note: Wood fuel users are for rural only, while unhealthy household variables denote average of rural-urban households. Unhealthy household building criteria: nonpermanent wall, earthen floor, insufficient ventilation and natural lightning, dense households (<8 m^2/person) for urban and rural area)

The level of indoor air pollution is closely related with physical housing characteristics. Due to enclosed environment, the housing characteristics and people's behavior inside the house will determine the exposure of pollutants to household members. Even though the total amount of pollutants inside the house is relatively small compared to that of outdoor, the exposure to pollutants is relatively higher than outdoor due to longer time spent inside.

Local housing characteristics were influenced by local wisdom, culture, climate, and location. Typically the households in mountainous area using wood fuel were potent to have the indoor air pollution episode than in coastal areas owing to smaller room volumes, longer cooking duration, smaller ventilation area and space heating need. In addition, the improper behavior in a large fraction of the mountainous people such as keeping close the ventilation during cooking incurs harmful pollutant exposure at higher risk.

Indoor air pollution concentrations in rural mountainous area on average were higher than those in coastal area (Huboyo 2013). This was due to bigger volume, sufficient ventilation, and less frequent cooking with wood fuel. The susceptible

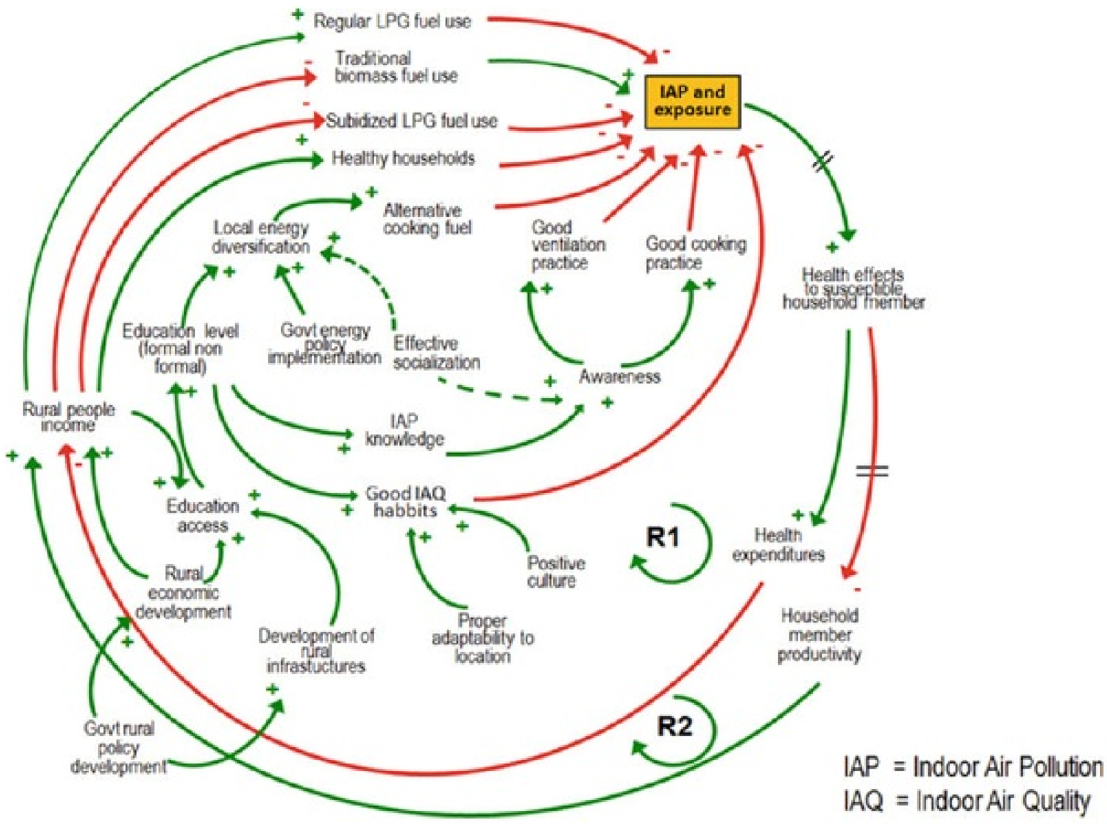

Fig. 20.5 Causal diagram analysis of indoor air pollution in Indonesian rural households

household members present in the kitchen were likely more exposed in the mountainous site than in coastal site due to smaller volume and inadequate ventilation. It is recommended to minimize activities in the kitchen during cooking period because most of the indoor PM2.5 mass size fraction was dominated in submicron size range which is respirable and poses a health threat.

Indoor air pollution episode in rural areas is rooted by persistent use of wood fuel with traditional wood stove in unhealthy household. The schematic root problems and probable solutions are illustrated in Fig. 20.5.

As the economic motive was behind this condition, therefore poverty alleviation as mandated in Millennium Development Goal (MDG) is the core to solve the problem. However, to eradicate rural poverty requires sustainable rural development in a long-term program. Then it needs, otherwise, immediate action (short term-program) to mitigate indoor air pollution within rural households. Furthermore, medium-term program is also needed to mitigate it to ensure reliable resources for infrastructure development, funding resources, and time for socialization. There are many ways to improve indoor air quality in rural area households; however, this proposed recommendation assumes the characteristics of the village are typical with those in this observed area.

20.3.3.1 Short-Term Program

The proposed program is based on current ventilation area availability to minimize the cost of changing ventilation scheme. This might be done by opening up the ventilation to dissipate the combustion pollutants as quickly as possible from the inner households and implementing good practice in cooking which should be familiarized by the cooks. The stove should be put near the ventilation to allow smoke exit, move intermittently to neighboring rooms during cooking, keep the interconnecting door between the kitchen and living room close, avoid putting plastic/waste garbage to include in the burning, prolong for keeping the wood stock/other biomass for cooking, and minimize the time of non-cooks to be in the kitchen during cooking.

20.3.3.2 Medium-Term Program

In this proposed program, several physical and nonphysical resources are needed. First is the installment of an improved (efficient) wood stove with chimney. These stoves should be provided by external funding scheme because most of rural people are poor. Second is diversification of cooking energy with adopting local resources such as biogas, biofuel, or other renewable energy. This program already exists under self-sufficient energy village program (Ministry of Energy and Mineral Resources). However, this should be fostered to reach as many as rural villages and emphasize on providing cooking energy, too (not only for providing electricity). Third is reorganizing the kitchen households by enlarging the kitchen to get a reasonable volume if sufficient ventilation could not be afforded or if possible separation from the dwelling room and promoting sustainable harvesting of wood fuel by only harvesting the branches of trees (not the trunk) to prevent biomass resource depletion. Last is giving socialization on healthy cooking and healthy living and wise use of cooking energy.

20.3.3.3 Long-Term Program

Alleviate the poverty by giving access of rural people on education, developing adequate basic infrastructures, providing health services, and securing clean energy as well as electricity. Healthy living will be achieved if there are enough opportunities for rural people to be empowered. Helping rural people to maintain their livelihood and raise their incomes without depending on subsidized fuel will establish the balance of urban-rural growth. Other issue is the change of persistent habits which should be broken. Change the inappropriate habits leading to deteriorating indoor air quality such as smoking, using mosquito coil burning (using a lotion or electric mosquito repellant instead), burning the garbage, and applying space heating with wood stove combustion.

20.4 Conclusion

The relative risk of cardiopulmonary and cardiovascular diseases was higher in the mountainous site than in the coastal site due to the former having worse kitchen environments and longer exposures than did the coastal area. The calculated risks for the cooks using wood fuel for cooking in the mountainous site are comparable to those found by other researchers. A single box model can be used for roughly estimating indoor air pollution from using wood fuel when cooking. The ratio of simulated concentrations to actual concentrations was better for the Lembang site, i.e., 0.9 and 1.7, compared to for the Juwana site, i.e., 1.13 and 1.8, for the wet and dry seasons, respectively. Overall, this model is quite useful to preliminarily assess the indoor air pollution that might occur if housing parameters are well characterized. Reflecting on this work, countermeasures for mitigating indoor air pollution in these areas should be prioritized as reducing pollutants at their sources, such as installing improved wood stoves, providing or practicing sufficient ventilation to expel the pollutants out of the houses, and improving the quality of the living environment by separating the kitchen from the main building.

Adoption of dual fuel energy (LPG-wood fuel) in rural areas is mainly driven by economical motive; therefore, poverty alleviation as mandated in Millennium Development Goal (MDG) is the core to solve the problem. To solve the problem comprehensively, it needs long-term, medium-term, and short-term program. Eradicating rural poverty requiring sustainable rural development is a long-term program. Medium-term program is also needed to mitigate it to ensure reliable resources for infrastructure development, funding resources, and time for socialization. The immediate action (short-term program) is to mitigate indoor air pollution within rural households as much as possible by ventilation arrangement and good cooking practice implementation.

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